LCA Methodology

Application of the Impact Pathway Analysis in the Context of LCA

The Long Way from Burden to Impact

Wolfram Krewitt, Petra Mayerhofer, Alfred Trukenmüller, Rainer Friedrich

Institut für Energiewirtschaft und Rationelle Energieanwendung, Universität Stuttgart, Heßbrühlstr. 49 a, D-70565 Stuttgart, Germany

Corresponding author: Dr.-Ing. Wolfram Krewitt; e-Mail: Wolfram.Krewitt@ier.uni-stuttgart.de

Abstract

Current LCA practice is mass oriented, i.e. is focused on the amount of chemicals released, disregarding place and time of release. Life cycle impact assessment aims at evaluating potential impacts, and a variety of weighting schemes is discussed to be used for ranking and aggregation of impacts. To establish a closer link between the quantity of a burden released and a decision making context, we propose to follow a detailed impact pathway analysis to estimate actual impacts for some priority impact categories, and use measured individuals' preferences for impact valuation. Results from a case study illustrate the relevance of site specific impact assessment in the context of LCA.

Keywords: Impact pathway analysis, application; impact valuation; LCA, from burden to impact; LCA, practice, mass oriented; LCA; Life Cycle Assessment (LCA); priority impact categories; site specific impact assessment

1 Introduction

Life Cycle Assessment is well accepted now as an important tool supporting decision processes in the field of environmental policy. Over the last years, a large number of LCA studies have been performed, setting up detailed inventories covering several hundreds of environmental burdens from a large number of individual processes. Although results from these studies are considered as a big step forward, their actual implication on the decision making process is not always obvious. Even without setting up a detailed Life Cycle Inventory for energy systems, it is e.g. not surprising that CO_2 emissions from fossil power generation are by far higher than from nuclear energy. On the other hand, even the most detailed quantification of greenhouse gas emissions and radionuclides released does not give any advise on society's acceptance of the related impacts. Although this is a very simplified example, it clearly shows that the decision making process needs to bridge the gap between the emission inventory and society's perception of environmental damage.

Only if the LCA framework succeeds in linking the inventory data to the relevant decision making context in an appropriate way, it will come up to the high expectations set towards the LCA approach. Unfortunately, the current LCA practice is still rather weak in this specific area. While the process of standardizing the methodology for inventory assessment is well advanced on the international level, there exists a variety of different approaches for impact assessment and valuation in the literature, which do not yet appear to be very well harmonized. This is certainly due to the complex nature of the impact assessment and valuation procedure as such. On the other hand the wide range of problems that are addressed within LCA studies, covering product improvement on the firm level as well as the evaluation of national environmental policy strategies, suggests that there might be reasonable alternative approaches for different questions.

The approach of *Impact Pathway Analysis* described in the present paper has been developed within the EU funded ExternE Project on External Costs of Energy (EUROPEAN COMMISSION, 1995) to support the quantification and valuation of environmental impacts resulting from electricity generation technologies. In contrast to other methods for impact assessment discussed in the context of LCA, the impact pathway approach attempts to quantify the "actual" effect resulting from the exposure to a burden at a specific place and time, rather than estimating a "potential" impact. The approach of impact pathway analysis has been successfully used for a comparative assessment of environmental damage resulting from electricity generating and transport technologies, as well as for the evaluation of environmental policy measures in the energy field.

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2 Impact Pathway Analysis as a Tool for LCA Impact Assessment and Interpretation

2.1 Methodology

"The impact assessment phase of LCA is aimed at evaluating the significance of potential environmental impacts using the results of the life cycle inventory analysis. In general, this process involves associating inventory data with specific environmental impacts and attempting to understand those impacts." (ISO, 1997)

To understand the association between environmental burdens and resulting impacts, the impact pathway analysis attempts to describe the chain of causal relationships from the emission of a burden through transport and chemical conversion in the environment to the impact on various receptors, such as humans, crops, building materials or ecosystems. The impact caused by a unit pollutant emitted at a specific site depends on site specific parameters like e.g. the meteorological conditions, the population density and the background concentration of pollutants, which all have to be taken into account for impact assessment. As the chain of effects from emission to damage in some cases is extremely complex, it has to be simplified to allow the operationalization within a modeling framework. To allow implementation, an impact pathway is broken down into the stages shown in **Figure 1**. While in the LCA inventory analysis environmental burdens can be quantified reasonably accurate, uncertainties are increasing step by step towards the valuation stage.

Looking at a product's full life cycle, there is practically an infinite number of individual impact pathways, each of which describing the potential impact resulting from a specific burden. However, it is quite obvious that even within a comprehensive technology assessment no-one will be able or even willing to trace back all these possible impact pathways. Taking into account the overall uncertainties of the impact assessment and valuation stage, it is in general sufficient to identify priority impacts which are expected to cause the major environmental damage, and thus are of most relevance for valuation. The identification of priority impacts has to be based on a careful review of the relevant literature, but is implicitly based on a first value judgment and in some cases needs an iterative procedure. Because of the complexity of a site specific impact pathway analysis the approach described in the present paper is currently limited to airborne pollutants.

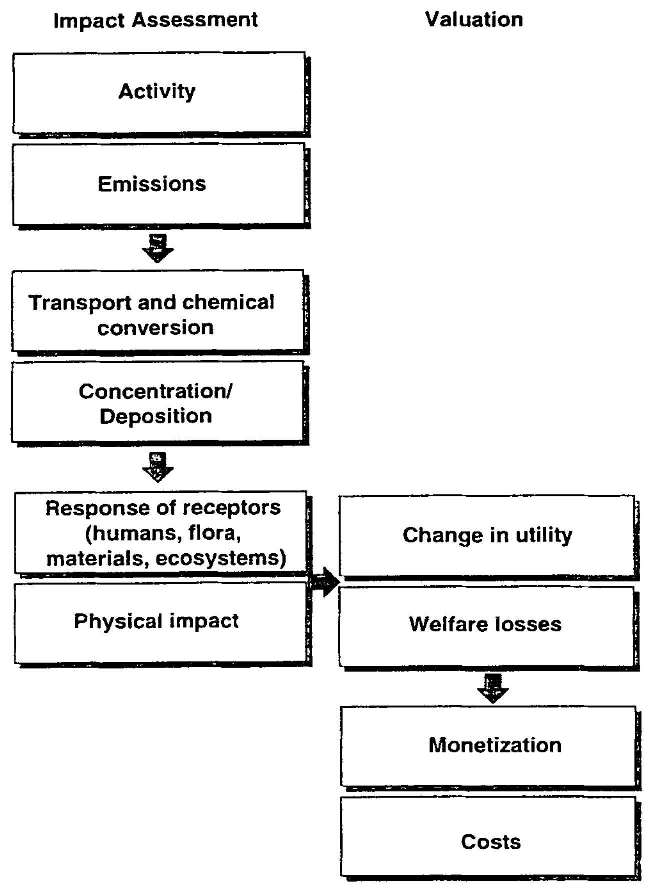

Fig. 1: Structure of an impact pathway

2.1.1 Quantification of impacts

The change in concentration levels of ambient air pollution resulting from the operation of an emission source in turn leads to a response at various receptors, which we try to describe by using a set of exposure-response models. As in most cases our current understanding is not sufficient to understand the complex biochemical mechanism of action, we have to rely on statistical correlations that have been observed between exposure and effect. However, detailed research is required before a dose-response relation can be considered as valid. Study reliability, adjustment for confounding factors, consistency of findings across different circumstances, and biological plausibility are all relevant to interpreting an association as causal or not. Of course the approach can handle only those impacts for which a causal link between burden and impact has been established. There is no need for any site specific impact assessment for globally acting pollutants like greenhouse gases or substances contributing to stratospheric ozone depletion, so that these impact categories are not addressed within the framework of impact pathway analysis, although they certainly are priority impacts with a strong relevance for valuation.

2.1.2 Health effects

There are now numerous studies linking ozone and fine particulate air pollution with a wide range of both acute and chronic health effects, and there is a growing tendency to treat the associations as causal. Incremental particulate air pollution may arise due to the direct emissions of parti-

culates, but also due to the subsequent formation of sulphate and nitrate aerosols from gaseous SO_2 and NO_x emissions. From recent epidemiological studies (POPE et al., 1995), there is an increasing evidence of chronic mortality effects from ambient particulates. In contrast to the time series studies on acute mortality (SCHWARTZ, 1993), which show a correlation between day-to-day changes in ambient air particulate concentration and daily death rates, studies on chronic mortality give a change in age-dependent mortality rate within the total population resulting from long term exposure to an increased level of air pollution. Using this measure, we can quantify the cumulated loss of life expectancy within the population rather than the number of "additional" deaths. (Taking into account the fact that everybody dies only once, the quantification of "Years of Life Lost" due to air pollution seems to be more appropriate than counting "additional" deaths.) The application of the change in age-dependent mortality rate as a function of ambient particulate concentration from e.g. POPE et al. to a European population results in a relation between a change in ambient concentration and reduced life expectancy, measured as "Years of Life Lost" (HURLEY et al., 1997).

For carcinogens, including some heavy metals and a range of hydrocarbons, the epidemiological evidence is much weaker than for the "classical" pollutants. There exist a number of unit risk factors published by bodies like the World Health Organization, the US Environmental Protection Agency or the German Länderausschuß für Immissionsschutz (LAI), which can be used as a dose-response function. However, unit risk factors recommended by different organizations might differ by more than an order of magnitude, indicating the large range of uncertainty related to cancer risk assessment. As our modeling framework (→ *section* 2.2) is currently limited to airborne pollutants, we used data from the literature on the ratio between direct inhalation and intake via food chain for different heavy metals to estimate the additional effects resulting from exposure via the food chain.

2.1.3 Effects on agriculture

Exposure-response functions describing direct effects of SO_2 and ozone on crop yield have been derived from a large number of field exposure or open-top chamber experiments. Furthermore, the costs of changing the amount of lime needed to deal with acidification of agricultural soils, and the benefits of N deposition acting as fertilizer can be estimated following an approach described in (HORNUNG, 1996).

2.1.4 Effects on building materials

The dose-response functions for the effects of SO_2, ozone and wet acid deposition on corrosion are mainly taken from the work of the UN-ECE ICP on materials (KUCERA et al., 1995). The thickness or mass loss calculated by using these dose-response functions leads to an estimate of changes in the maintenance and replacement effort. The material inventories are quantified in terms of the exposed material area from estimates of 'building identikits' (representative buildings). Surveys of materials used in the buildings in some European cities (Birmingham, Cologne, Dortmund, Sarpsborg, Stockholm, and Prague) were used to take into account the use of different types of building materials around Europe.

2.1.5 Effects on ecosystems

Especially for ecosystems the impact processes are very complex. A multitude of organisms and influencing factors interact, causing synergistic and accumulative effects that cannot safely be predicted if they are not governed by one effect already identified and studied in the past. For such effects and processes, which can be described only qualitatively, thresholds can be identified. If e.g. air pollution levels stay below these thresholds no effects are expected. Such an approach is consistent to the concept of sustainable development, namely the so-called third management rule which requires that the assimilative capacity of ecosystems should not be jeopardised (PEARCE and TURNER, 1990). Thresholds have to be defined for each receptor and potential effect, clearly specifying temporal and spatial dimensions. One example for such thresholds are the critical levels and loads for different plants and ecosystems developed in the framework of the Convention on Long-Range Transboundary Air Pollution of the UN-ECE (POSCH et al., 1995).

2.1.6 Valuation

If alternative technical options lead to environmental impacts on different impact categories, a weighting scheme is required that allows a comparison across environmental themes. While there exists a wide range of approaches to valuation in LCA (POWELL et al., 1997), (FINNVEDEN and LINDFORS, 1997), our current work is focused on monetary valuation, thus attempting to use individuals' preferences as a basis for the allocation of weighting factors. Based on the concepts of welfare economics, monetary valuation of environmental impacts follows the approach of *Willingness-to-Pay* for improved environmental quality or *Willingness-to-Accept* environmental damage.

The concept of monetary valuation is often criticized from an ethical point of view, in particular for assigning a monetary value to human life. It is argued that monetary valuation neglects the perceived "right" of not be subjected to physical harm by other people, and that people would put an infinitely high value on an individual's life. Actual behavior shows however that both individuals and legal authorities carefully weigh the costs and benefits of investments in e.g. transport safety. Nearly all decisions include both a change in risk and costs, so that implicitly a trade-off between costs and risks is often made. Monetary values for avoiding or reducing the risk of mortality and morbidity are derived from individual

preferences revealed by their market behavior or by contingent valuation surveys (see e.g. (EUROPEAN COMMISSION, 1995) for a more detailed discussion of valuation techniques). The so called *Value of Statistical Life* (VSL) is used as a measure for welfare losses caused by the risk to life. It is derived by dividing the average *Willingness-to-Pay* for a certain risk reduction by the size of that risk reduction (e.g. if the *Willingness-to-Pay* is 100 $ for a mortality risk reduction of 1 in 10 000, the Value of Statistical Life is 1 Million $). It is important to emphasize that the VSL is not a measure for the value of an individual's life, it is rather based on an ex-ante valuation referring to the statistical risk before the damage takes place. Taking into account the change in age specific deaths rate due to a specific burden and the age distribution within a European reference population, we have calculated a *Value of Life Year Lost* to put a value on the reduction in life expectancy rather than on the loss of life.

Although recognizing the methodological problems related to monetary valuation, it is the only current approach that attempts to empirically measure individuals' preferences which can be aggregated over different impact categories and thus provides an as far as possible "objective" relative weighting between impacts (as it uses measured preferences of the affected population). In the case of impacts on ecosystems which we are currently not able to value, we follow a distance-to-target technique by calculating the additional exceedance of critical loads/levels of a specific activity.

2.2 Implementation of the Impact Pathway Analysis within the *EcoSense* Model

The implementation of the impact pathway approach described above requires the availability of a range of specific models as well as the capability of handling a large quantity of data. To support a standardized application of the impact pathway analysis, we have developed the integrated impact assessment model *EcoSense* (KREWITT et al., 1995). *EcoSense* is a user-friendly Windows application providing most of the data and models required to carry out a site specific impact assessment (→ *Fig. 2*).

2.2.1 The *EcoSense* database

The core of the *EcoSense* database is the "Reference Environment Database", holding receptor data, meteorological data and emission data for the whole of Europe (→ *Table 1*). These data allow a site specific impact analysis at any site in Europe. Supported by an interactive interface, the user can define any exposure-effect model as a mathematical expression. The user-defined function is stored as a string in the database, which is interpreted by the respective impact assessment module at runtime. This concept, which makes the sytem a model-interpreter rather than a model, allows an easy updating of dose-response functions. With regard to the rapidly growing knowledge in the field of environmental impact mechanisms we consider this as an important feature of the system. The user can assign monetary values to each impact described by one of the dose-response functions which are also stored in the database.

2.2.2 Air quality modeling

To cover different pollutants and different scales, *EcoSense* provides three air transport modules completely integrated into the system:

- The Industrial Source Complex Model (ISC) is a Gaussian plume model developed by the US-EPA (BRODE and WANG, 1992). The ISC is used for transport modeling of primary air pollutants on a local scale.
- The Windrose Trajectory Model (WTM) (TRUKENMÜLLER and FRIEDRICH, 1995) is a user-configurable trajectory

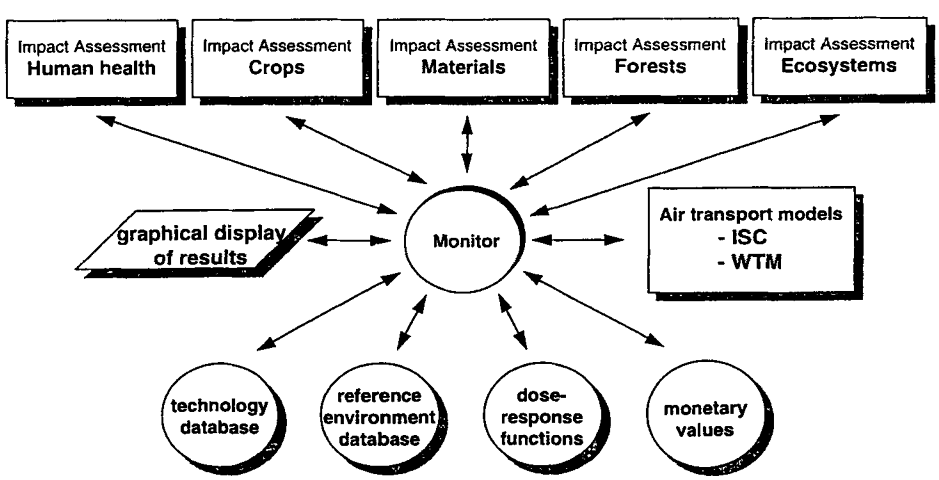

Fig. 2: Structure of the *EcoSense* model

Table 1: "Reference Environment" data included in the *EcoSense* databse

	Resolution	Source
Receptor distribution		
Population	EMEP 50 grid and 10 x 10 km	EUROSTAT REGIO
Production of wheat, barley, sugar beat, potato, oats, rye	EMEP 50 grid and 10 x 10 km	EUROSTAT REGIO
Inventory of natural stone, zinc, galvanized steel, mortar, rendering, paint	EMEP 50 grid	Extrapolation based on inventories of some European cities
Critical Loads/Levels for nitrogen-deposition for various ecosystems	EMEP 50 grid	UN-ECE
Meteorological data		
Wind speed	EMEP 50 grid	EMEP
Wind direction	EMEP 50 grid	EMEP
Precipitation	EMEP 50 grid	EMEP
Emissions		
SO_2, No_x, NH_3	EMEP 50 grid	EMEP

model based on the windrose approach of the Harwell Trajectory Model developed at Harwell Laboratory, UK (DERWENT, DOLLARD and METCALFE, 1988). For current applications, the WTM is configured to resemble the atmospheric chemistry of the Harwell Trajectory Model. The WTM is used to estimate the concentration and deposition of acid species on a European wide scale.

- The Source-Receptor Ozone Model, based on the EMEP country-to-grid matrices (SIMPSON et al., 1997), is used to estimate ozone concentrations on a European scale.

All input data required to run the Windrose Trajectory Model and the Source-Receptor Ozone model are provided by the *EcoSense* database. A set of site specific meteorological data has to be added by the user to perform local scale modeling using the ISC model. The concentration and deposition fields calculated by the air quality models are stored in the reference environment database.

2.2.3 Impact assessment modules

The impact assessment modules calculate the impacts and – as far as possible – the resulting damage costs by applying the exposure-response functions selected by the user to each individual gridcell, taking into account the information on receptor distribution and concentration levels of air pollutants from the reference environment database. The assessment modules support the detailed step-by-step analysis for a single endpoint as well as a more automized analysis including a range of pre-specified impact categories. Input data as well as intermediate results can be presented on several steps of the impact pathway in either numerical or graphical format. Geographical information like population distribution or concentration of pollutants can be presented as maps. *EcoSense* generates a formatted report with a detailed documentation of the final results that can be imported into a spreadsheet program.

2.2.4 Uncertainty

Following the impact pathway from emission to valuation, there is certainly an increasing level of uncertainty involved in the models used for impact assessment and monetisation of effects. Within the ExternE study, a detailed assessment of uncertainties was carried out by [RABL, 1997], giving an estimate of confidence intervals for each stage of the impact pathway. There is however a remaining systematic uncertainty driven by a set of "strategic assumptions" e.g. on the existence of threshold values or on the valuation of a Statistical Life versus Life Years Lost, which are difficult to quantify. *EcoSense* is a helpful tool to analyze the influence of such assumptions in a formal sensitivity analysis.

2.3 Does a bottom-up impact pathway approach fit into the LCA context?

Current LCA practice is mass oriented, i.e. the method focuses on the amount of chemicals released, disregarding place and time of release. A *potential* impact of a burden which does not depend on site nor time is calculated by using a set of characterization factors. Several authors explicitly emphasize that for both methodological and practical reasons it is not the objective of LCA to establish an association between emission and the "real" impact. As it is however the anticipated *actual* impact which is of relevance for any valuation or decision making, we would not like to follow this methodological limitation, although we do recognize the need for simplification in this complex field of environmental impact assessment.

The relation between a potential damage and the actual impact depends on various site specific parameters, and – as shown in the example given in section 3 – the impact per unit pollutant emitted might differ significantly across sites. In the case of reactive pollutants and of threshold concen-

trations the expected impact does obviously depend on the level of background concentrations of pollutants as well as on the composition of the pollutant mix. Also the site of the emission source might be of major importance: results show that there is a substantial difference between damage per unit pollutant emitted e.g. from a municipal waste incinerator which is operated close to an urban area, or from a power plant with a tall stack operated in a rural environment. The approach of impact pathway analysis can help to improve the accordance between the predicted impacts and the contribution of a product to the actual effect that can be observed, and thus from our point of view can reasonably supplement the current LCA valuation methodology. The use of air quality and exposure-response models allows – for some impact categories – a detailed description of the actual impact caused by a burden which is released at a given place and time. This precise characterization of impacts in turn allows a valuation that is based on empirically measured individuals' preferences towards a change in environmental quality.

While inventory data are available for hundreds of pollutants, the limitation to about 20 priority pollutants is of course not sufficient within the LCA context – there is an obvious need for the implementation of further impact pathways in the future, regarding the current work as a starting point. A comprehensive impact pathway analysis taking into account *all* environmental burdens will remain a prohibitive resource intensive undertaking, but from our point of view the quantification of a limited set of well defined priority impacts in many cases can give a reasonable and sufficient input to the decision making context.

To conclude, we will briefly discuss the impact pathway approach by using criteria defined by the German Federal Environmental Agency to check the practical applicability of LCA impact assessment tools (UBA, 1995):

- *Scientific objectivity*
  From our point of view, the modeling of the causal chain of effects from emission to impact does fulfill the criteria of scientific objectivity more than the approach of potential impacts, as it better takes into account site specific parameters that might significantly influence the actual impact. The use of monetary values that are based on empirically measured individuals' preferences should be preferred to weighting schemes derived from e.g. expert panels.

- *Applicability within the LCA context*
  A detailed impact pathway analysis taking into account site specific conditions in principle is very resource intensive. The approach presented here resulted from a close cooperation between experts from various disciplines over the last years within the ExternE programme. However, a large number of case studies has shown that the *Eco-Sense* software allows a standardized application of the methodology with a reasonable low effort, as air quality and impact models are provided by the system together with relevant input data (for Europe). The integration of additional impact pathways remains a costly task which has to be addressed by appropriate scientists rather than LCA practitioners.

- *Transparency of the approach*
  Although at a first glance the impact pathway approach seems to be rather complex and the aggregation to damage costs is a subject of common criticism, the step-wise analysis of the stages of the impact pathway from emission via concentration/deposition to impact allows a transparent presentation of results. As detailed results are available on each stage of the impact pathway, the influence of different assumptions on the results which might reflect the current understanding of impact mechanisms can be easily analyzed.

3 Environmental Impacts from Electricity Generation - Results of a Case Study

Within the frame of the EC funded ExternE-Study on External Costs of Energy, the impact pathway approach has been applied in all EU countries to estimate environmental impacts and resulting external costs from electricity generation. We will briefly discuss some of the results to illustrate the output from an impact pathway analysis. A detailed description is given in (EUROPEAN COMMISSION, 1995).

Table 2 and **Table 3** show selected health and environmental impacts and resulting external costs from different electricity generating systems in Germany. Results refer to specific technologies operated at specific sites (FRIEDRICH and KREWITT, 1997) which were defined to allow a site specific impact pathway analysis. Following the approach of quantifying priority impacts, we have quantified emissions from the full fuel cycle, including fuel extraction and preparation, transport, electricity generation and waste disposal in the case of fossil and nuclear power generation. For photovoltaics and wind, emissions from material production and construction processes are also included. Although these differences in the treatment of fuel cycles is not fully consistent in the sense of LCA, from our point of view it is a pragmatic approach to quantify the most important impacts with a reasonable effort. By presenting examples of physical impacts in **Table 2** we want to point out the availability of disaggregated information for a wide range of impact categories that can also be used in valuation schemes different than monetization.

To illustrate the importance of site specifity, **Figure 3** shows damage costs per tonne of PM_{10} (particulate matter with aerodynamic diameter < 10 µm) emitted from power stations at different European sites. We use PM_{10} as a simple example, because it is a primary and non-reactive pollutant, so that the differences in damage costs per unit pollutant emitted is basically a matter of difference in receptor distribution and stack height. In principle, the damage costs per unit pollutant emitted

Table 2: Environmental impacts from selected electricity generation "fuel cycles" in Germany per kWh (Examples)

	Coal	Natural Gas	Nuclear	Photo-voltaic	Wind
Mortality					
Years of Life Lost	124	85	25.1	8	1.7
Morbiditiy, e.g.					
Restricted activity days	4264	1009	314	276	59
Chronic bronchitis in children	116	27	14.1	7.5	1.6
Respiratory symptoms	622	147	45	40	8.6
non-fatal cancer	-	-	2.4	-	-
Yield loss in t, e.g.					
wheat	104	1	3	13	3
potato	152	2	1	19	4
Material impacts, e.g.					
Zinc and galvanised steel replacement area in m^2	683	128	27	93	13
Repainting in m^2	10550	2786	418	1439	196
Ecosystems					
Change in critical load exceedance area times exceedance height in ‰ (nitrogen eutrophication)	0.087	0.033	0.012	0.027	0.0012

can be used in a similar way as the potential impact factors commonly used in the LCA valuation step, but **Figure 3** shows that the damage costs as an aggregated indicator of the *actual* impacts vary by more than an order of magnitude across European sites, thus emphasizing the need of a site specific impact assessment. To establish a standardized procedure for impact assessment in product LCA it is of course desirable to identify an appropriate level of generalization to avoid a detailed impact pathway analysis for each individual emission source. A first analysis of site dependency and the difference between average and site specific impacts is given in (KREWITT et al., 1998).

Table 3: Environmental damage costs from selected electricity generation fuel cycles in Germany (mECU/kWh)

	Coal	Natural Gas	Nuclear	Photo-voltaic	Wind
Public health effects[a]	7.7 - 49.2	2.5 - 14.5	0.26 - 7.2	0.87 - 1.6	0.18 - 1.2
Crop losses	0.004	0.0001	0.0004	0.0005	0.0001
Material damage	0.15	0.036	0.018	0.023	0.0031
Ecosystems			not quantified		

[a]Range of results is due to different assumptions in monetary valuation of mortality

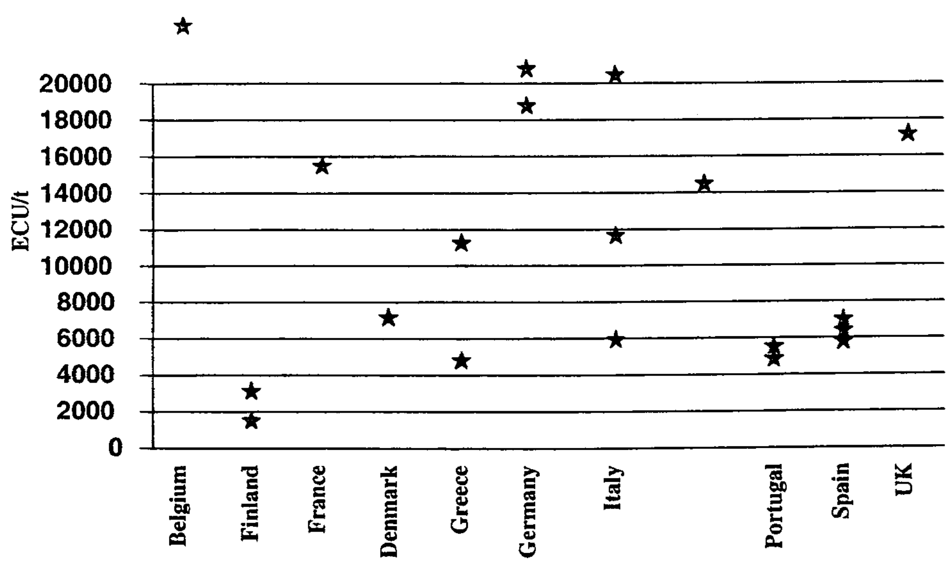

Fig. 3: Damage costs per tonne of PM_{10} emitted at different European sites

In a last example we want to show that in spite of the existing uncertainties monetary values can be very helpful for the evaluation of specific environmental policy measures. In contrast to potential impacts, aggregated damage costs can be directly compared with the costs of reducing environmental burdens. As an example, **Figure 4** compares the costs of reducing SO_2 emissions by using wet limestone flue gas desulphurization and the avoided damage costs per tonne of SO_2 emitted from a coal fired power plant operated in the South of Germany. Uncertainties are addressed by subsequently adding damage estimates with an increasing level of uncertainty to the bar that shows the avoided damage costs from the bottom to the top (crop losses, material damage, morbidity, mortality). This way of presentation helps the decision maker to reflect on the level of uncertainty that has to be accepted to justify a specific policy measure. Results show that for the reference plant best available SO_2 reduction technology can be justified even without considering the more uncertain mortality effects.

account the site specific context, are of importance for valuation. Rather then distinguishing between disciplines, the current LCA framework should be regarded as complementary to approaches like e.g. *Risk Assessment* or *Environmental Impact Assessment*, which all require a detailed emission inventory.

The impact pathway approach presented in this paper allows the quantification of environmental impacts and – for many of them – of resulting damage costs, taking into account site specific conditions. Experience from case studies in all European countries shows that the *EcoSense* model allows a highly standardized and efficient application of the methodology. *EcoSense* currently supports a detailed impact pathway analysis for about twenty airborne pollutants. We consider this as a good starting point and will include further "priority pathways" in the future.

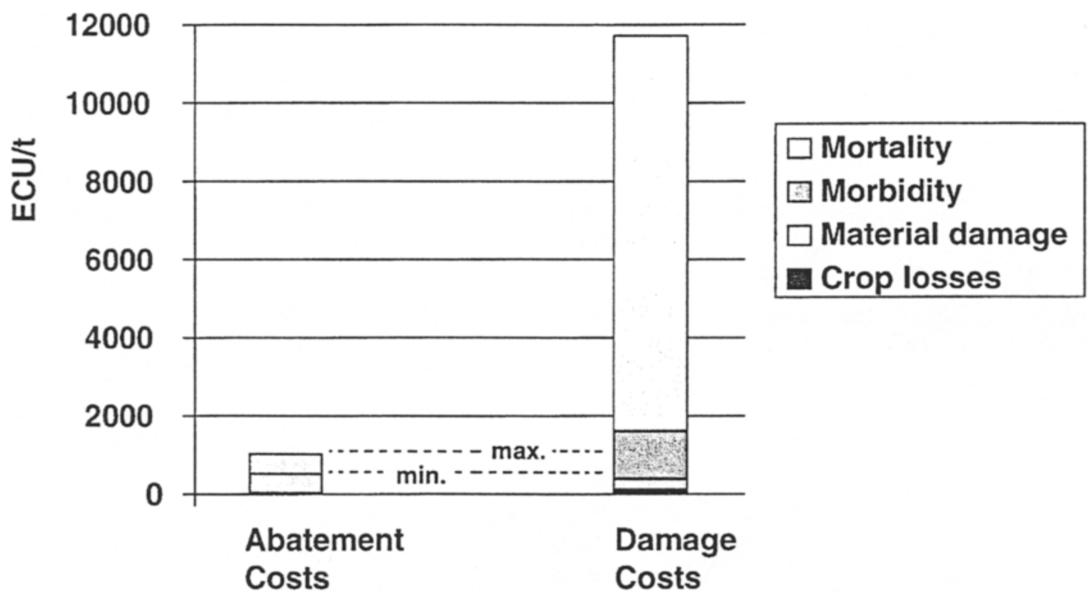

Fig. 4: Comparison of abatement costs and damage costs per tonne of SO_2 emitted from a coal fired power plant in Germany

4 Conclusions

While the methodology for LCA inventory assessment has achieved a satisfying level of standardization, there still exists a variety of different approaches for impact assessment and valuation which are not yet very well harmonized. This is a major drawback, as the development of very detailed emission inventories is of limited use if the LCA framework fails to establish a close link to the decision making context. From the authors' point of view, the explicit restriction to *potential* impacts in current LCA methodology is not very helpful, as in many cases the *actual* impacts, taking into account the site specific context, are of importance for valuation.

As far as applicable, we consider the approach of monetary valuation as the most appropriate way of weighting and aggregating different impact categories. Monetary values expressing individuals' preferences towards a wide range of health and environmental impacts are available from empirical studies. The use of such values for aggregation has advantages compared to weighting schemes derived from e.g. air quality standards or expert judgment, as the weighting is based on "measured" preferences. Furthermore, monetary values have the advantage of being more illustrative than "utility points" or other measures, although the results might be the same.

Uncertainties related to impact assessment and valuation are certainly large compared to those of the LCA inventory. Sometimes it seems that a detailed impact pathway analysis rises more questions than it gives answers (e.g. on the existence of thresholds, discounting of future impacts, valuation of mortality). However, these problems are of relevance for any valuation scheme, though they are not always explicitly addressed in such a systematic way. The impact pathway approach allows the analysis of different assumptions and value judgments on any stage of the impact pathway, so that their respective influence on results can be considered in valuation and decision making.

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